Type II-P supernovae in the mid-infrared

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I. Unpublished supernova data in the *Spitzer* database

Core-collapse supernovae (CC SNe), especially **type II-plateau (II-P)** ones, are thought to be important contributors to **cosmic dust production**. The most obvious indicator of the presence of newly-formed or pre-existing dust is the **time-dependent mid-infrared (MIR) excess** coming from the environment of SNe. In the past few years several CC SNe were monitored by the ***Spitzer Space Telescope*** in the nebular phase, hundreds of days after explosion. On the other hand, there have been only a few of these objects analyzed and published up to now.

Our goal was to collect publicly available, previously unpublished measurements on type II-P (or peculiar II-P) SNe from the *Spitzer* database. The most important aspect was to find SNe observed with the ***Infrared Array Camera (IRAC)*** on at least two epochs. The temporal changes of the observed fluxes may be indicative of the underlying supernova, while SED fitting to the fluxes in different IRAC channels may reveal the physical parameters of the mid-IR radiation, due to presumably warm dust.

Finally, we found **twelve SNe** satisfying the criterion above, observed at late-time epochs (typically >300 days). In three cases, ***SNe 2003hn***, ***2005cs*** and ***2006bc***, we could not identify any point source at the SN position on late time IRAC images. For the other nine SNe (Fig. 1) we carried out a complete analysis.

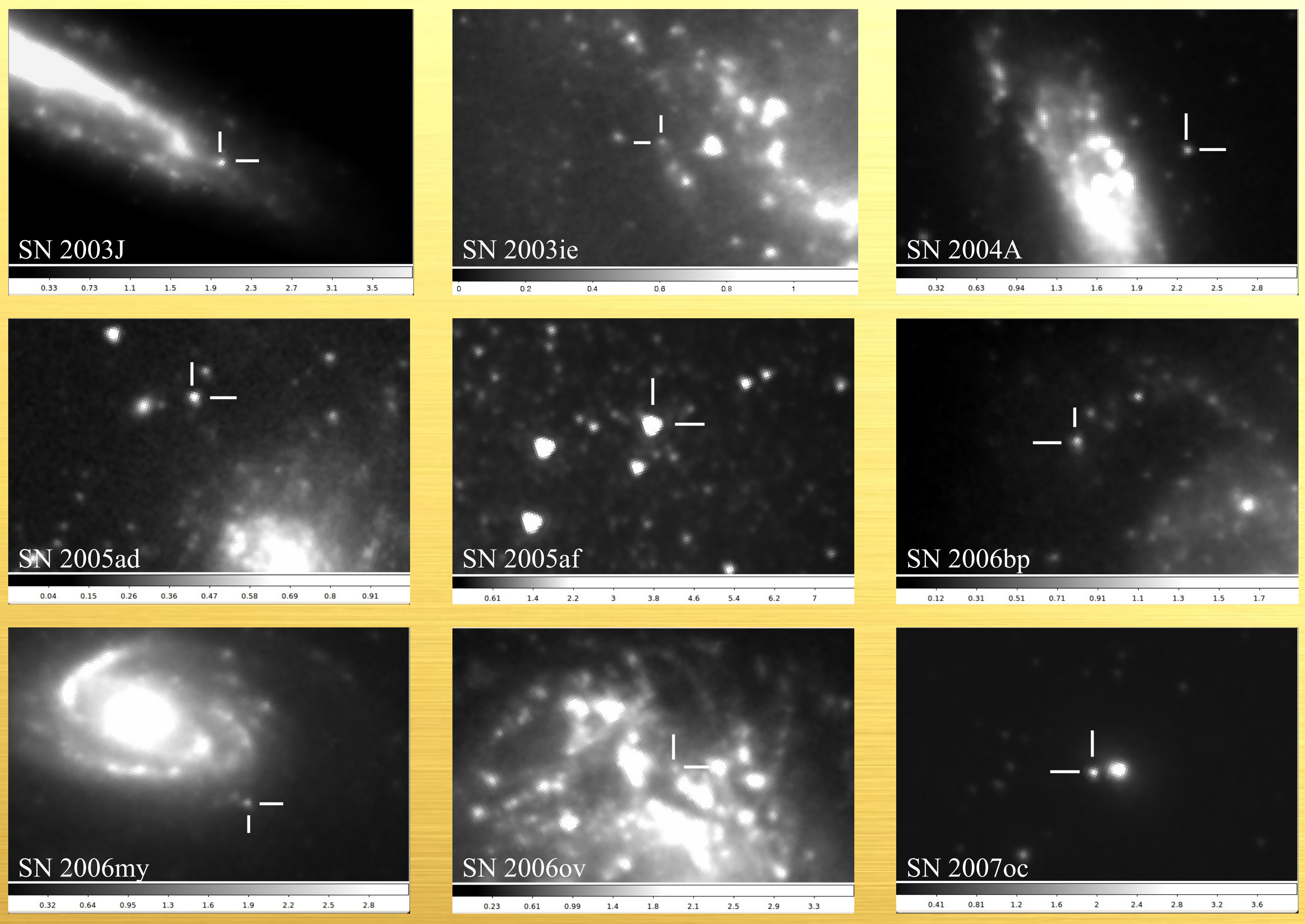

Fig. 1. *The studied type II-P SNe on IRAC post-BCD 4.5 μm images. The FOV is 100"× 60". North is up, and East is to the left.*

II. Analysis of mid-IR data

We carried out simple **aperture photometry** on the IRAC post-BCD frames with the *phot* task in IRAF, taking into account all IRAC-specific corrections. We also carried out photometry on *MIPS* (Multiband Imaging Spectrometer) 24.0 μm and *IRS* PUI (Infrared Spectrograph, peak-up imaging mode) frames using IRAF and MOPEX, respectively. The available IRS spectra were processed using SPICE.

Figure 2 shows the mid-IR SEDs of the studied SNe calculated from IRAC 3.6, 4.5, 5.8, and 8.0 μm fluxes (plotted with available PUI 13.0-18.5 μm and MIPS 24.0 μm fluxes). The continuum fluxes of reduced IRS spectra match well with the SED flux levels. Early-time MIR fluxes of SN 2005af, which are the only data already published elsewhere (Kotak et al. 2006), are also in good agreement with our values, supporting the accuracy of our measurement method.

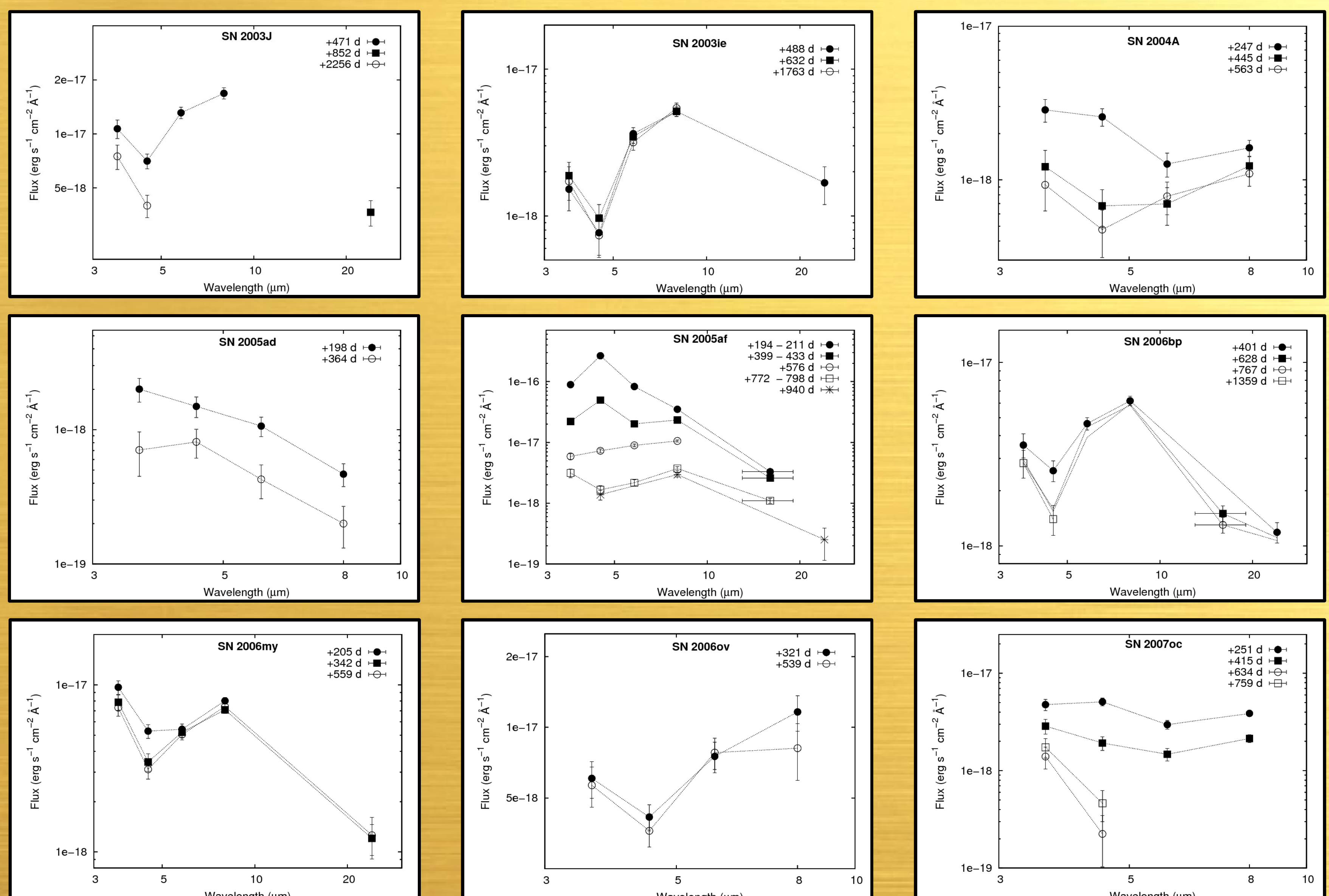

Fig. 2. *Mid-IR SEDs of the nine studied CC SNe at different epochs.*

III. Blackbody and dust model fitting to MIR SEDs

Assuming that the radiation is purely thermal, the main source of mid-IR flux is most likely **warm dust**. In order to derive the physical properties and estimate the total amount of dust, we fitted **blackbodies (BBs)** and **analytic dust models** to the observed SEDs. Prior to fitting, the observed SED fluxes were dereddened using the galactic reddening law parametrized by Fitzpatrick & Massa (2007) assuming R_V = 3.1 and adopting $E(B-V)$ values from the literature.

We fitted simple analytic models to the observed MIR SEDs using Eq.1 in Meikle et al. (2007) assuming a homogeneous (constant-density) dust distribution. To estimate the dust optical depth, we adopted the **power-law grain-size distribution** of Mathis, Rumpl & Nordsieck (1977, MRN) assuming m = 3.5 for the power-law index and grain sizes between a_{min} = 0.005 μm and a_{max} = 0.05 μm.

The dust is assumed to be distributed uniformly within a sphere. The **radius of the sphere (*R*)**, **grain temperature (*T*)**, and the **grain number density scaling factor (*k*)** were free parameters during the fitting.

Basically we used **amorphous carbon (AC) grains** (Colangeli et al. 1995) with ρ_{grain} = 1.85 g cm^{-3} (Rouleau & Martin, 1991), but in the cases of SNe 2005af and 2006my adequate solution was possible only by applying **Si-containing dust** (C-Si-PAH mixture, ρ_{grain} = 3 g cm^{-3}, Weingartner & Draine 2001). The main parameters of the best-fit warm dust models are shown in Table 1.

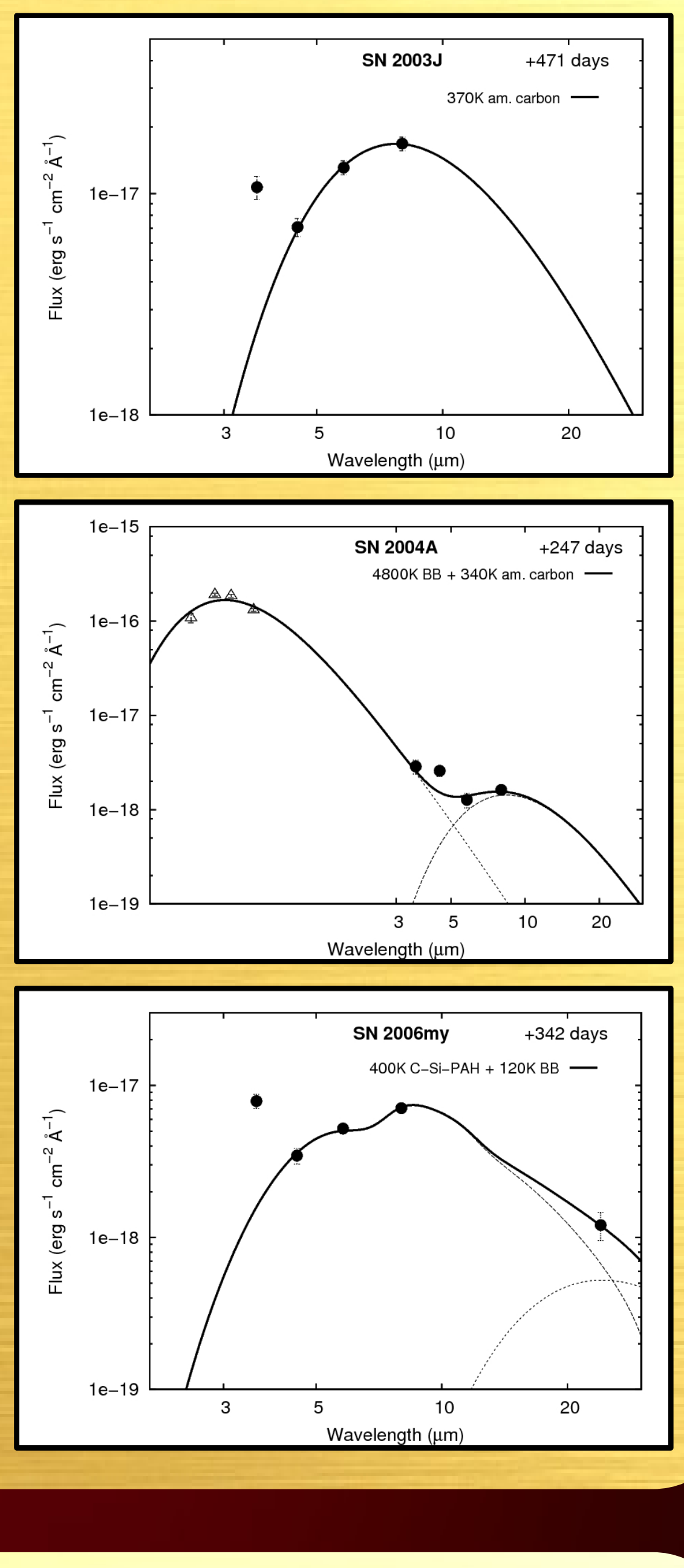

Fig. 3. *Examples of different kinds of SED models.* ***Top:*** *One warm component, AC model, SN 2003J (+471 days).* ***Middle:*** *AC warm + hot BB components (optical fluxes adopted from Hendry et al. 2006), SN 2004A (+247 days). The excess flux at 4.5 μm is most likely from the 1-0 vibrational band of CO.* ***Bottom:*** *C-Si-PAH warm + cold BB components, SN 2006my (+342 days).*

	T$_{warm}$ (K)	**R$_{warm}$** (10^{16} cm)	**v$_{BB}$** (km s^{-1})	**L$_{warm}$** (10^{39} erg s^{-1})	**M$_{dust}$** (10^{-5} M$_{Sun}$)
SN 2003J	370	6.4	15,500	48.8	710
SN 2003ie	310 … 280	6.2 … 15.8	14,400 … 4000	22.2 … 16.9	700 … 200
SN 2004A	310 … 370	3.9 … 2.2	15,900 … 4500	8.5 … 6.2	160 … 200
SN 2005ad	**890 … 750**	**0.4**	**1800 … 600**	**4.9 … 1.8**	**1.0 … 0.4**
SN 2005af*	**550 … 390**	**1.1 … 0.8**	**4800 … 700**	**4.3 … 1.5**	**21.0 … 8.1**
SN 2006bp	370 … 330	4.6 … 6.1	13,000 … 7700	26.2 … 29.3	480 … 1000
SN 2006my*	380 … 400	8.0 … 5.5	21,400 … 8700	44.9 … 28.4	920 … 1900
SN 2006ov	350	5.1 … 8.2	18,400 … 7300	25.9 … 15.4	650 … 82
SN 2007oc	340	8.9 … 5.5	26,300 … 13,700	37.8 … 23.5	310 … 370

Table 1. *Ranges of main parameters of the best-fit warm dust models. The velocities are calculated from the fitted blackbody radii which represent the minimum sizes of the dust shell at different epochs. SNe 2005af and 2006my (marked with asterisks) were fitted with C-Si-PAH mixture, while all other objects are modeled with AC dust.*

IV. Conclusions

With the nine studied objects, we **almost doubled** the number of type II-P SNe having detailed MIR data analysis based on *Spitzer* measurements. In two cases, **SNe 2005ad** and **2005af**, we found cooling temperatures and decreasing luminosities of the warm component which are similar to the values found in other SNe that are thought to have newly-formed dust in their environment (e. g. SN 2004et – Kotak et al. 2009; SN 2004dj – Szalai et al. 2011, Meikle et al. 2011).

As seen in Table 1, the calculated temperatures for the other SNe do not show strong temporal variation, while the derived luminosities as well as radii, are too high to be compatible with local dust. Also, the calculated dust masses in these cases are orders of magnitudes higher than the observed amount of dust around well-studied SNe listed above. The large radius of the warm component may suggest pre-existing dust in these cases, thus it is less likely that new dust is formed around these SNe.

Nevertheless, theoretical models predict orders of magnitude more, 0.1-1 M$_{Sun}$ of newly-formed dust in CC SNe. Our conclusions support the previous observational results that **warm new dust** in the environment of SNe **contributes only slightly to cosmic dust content.** A more important contributor, as latest results suggest, may be the colder (<50 K) dust which could be found in older SN remnants (see e. g. Matsuura et al. 2011).

Questions? Comments?
Please let me know!

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